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Realization of data flow in QCA tile structure circuit by potential energy calculation

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Abstract

Quantum Dot Cellular Automata is one of the popular alternatives of CMOS technology. QCA technology has higher clock speed upto tetra hertz range, lesser area then CMOS and unlike charge dissipation QCA technology is based on charge confinement. In this paper we had proposed an algorithm for data flow in QCA circuits. The algorithm is based on potential energy of the dots of a QCA cell. With this algorithm the operation of any QCA based complex design can be evaluated using potential energy calculation. In this paper at first we had proposed the operation of basic QCA majority voter using this proposed algorithm. We have further evaluated the working principle of QCA tile structure based on the proposed algorithm.

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Keywords: Quanum dot cellular automata; Potential energy; Kink energy; QCA majority voter; QCA tile structure.

1. Introduction

Quantum Dot Cellular Automata, better known as QCA, is one of the most promising alternatives of CMOS in the field of nanoscience for low power consumption and high speed operation in future generation computer circuits [Dehghan (2014), Lent and Gregory (2014), Yao et al (2014)]. QCA circuit is made up of several QCA cells placed in a specific manner over a substrate. Each QCA cell has four dots at the four corners. Extra electrons are injected at the two diagonal dots of the cell. A QCA cell thus has two polarizations viz. +1 for right diagonal position of

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electron and -1 for left diagonal position of electron [Ercan and Anderson (2014)]. Recently some experimental demonstrations of QCA based circuits have been reported [Bernstein (1999), Martinez et al (2008), Orlov et al (1997), Perez-Martinez (2008)].

Data transfer through QCA cell occurs due to columbic interaction between the electrons of the neighboring cells. In this paper we had presented data flow in QCA tile structure [Das and De (2011), Farazkish et al (2008)] which is used for compact and area efficient design for various specialized gates like AOI, NNI, XOR and XNOR gates. In our work we had done the realization of the working principle of QCA tile by energy model. Here an algorithm for realizing the QCA circuit operation had been proposed. This algorithm is based on potential energy model of QCA cell. By using this algorithm we can more accurately justify the data flow in between QCA cells and the operation of various QCA gates. Also we have compared our calculated values with the simulated values done by QCADesiner software.

Nomenclature

QCA	Quantum Dot Cellular Automata
AOI	AND-OR Inverter
NNI	NAND-NOR Inverter
I/P	Input port
O/P	Output port

1.1. Background on QCA

QCA cell is shown in Fig. 1(a). Each QCA cell consist of four dots, marked in the figure as A, B, C and D respectively. Extra electron gets confined in two of these dots. As a result of columbic interaction electrons gets confined either in dots A and C or B and D forming +1 and -1 polarization respectively [Dey (2014), Sen (2014), Ercan and Anderson (2014)]. In QCA technology placement of cell is crucial. By placing an array of QCA cell it is possible to create a wire. This is because the polarization of the 1st QCA cell will get propagated through the array. QCA wire is shown in Fig. 1(b).

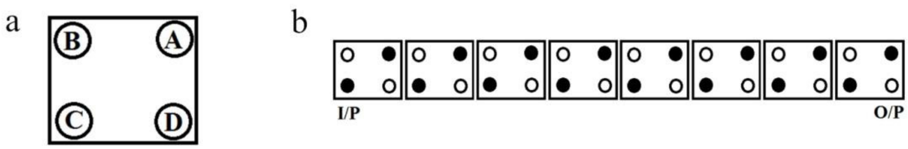

Fig. 1. (a) QCA Cell with 4 Dots numbered A, B, C and D, (b) QCA wire.

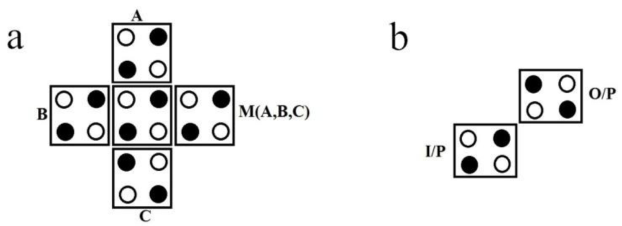

Fig. 2 (a) QCA Majority Voter; (b) QCA NOT gate.

In CMOS technology different arithmetic and logical operations are performed by Logic Gates. In QCA logic gates are represented by Majority Voter structure [Navi et al (2010)] and QCA based NOT gate. Fig. 2(a) and 2(b) shows the QCA three input Majority Voter and NOT gate respectively. With the help of 3-Input Majority Voter, AND and OR gates can be designed. The basic working principle of Majority Voter is that the output will follow the majority of the input, thus the name is Majority Voter.

$$MV(A,B,C) = AB + BC + CA \tag{1}$$

1.2. QCA Tile Structure

Tile structure is $N \times N$ array of fully populated QCA cell array, shown in Fig. 3. Every cell having dimension $18\text{nm} \times 18\text{nm}$ and the dot diameter is 5nm. The distance between two adjacent cells is 2nm. The details of the tile structure are discussed in [Das and De (2011), Ganesh (2010), Huang (2007)]. Different complex gates such as AOI, NNI, XOR and XNOR can be designed by using QCA orthogonal tile or by cascading two orthogonal tiles. In this paper we have considered one QCA tile based XOR gate.

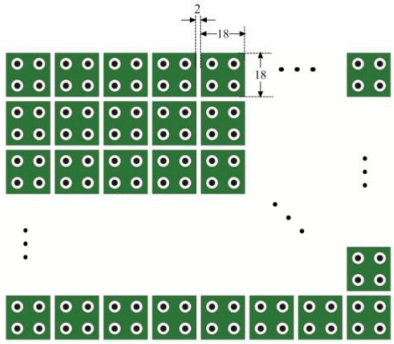

Fig. 3. QCA tile structure with $N \times N$ QCA cell array.

2. Proposed Algorithm for Potential Energy Calculation

We have proposed an algorithm for the energy calculation of a QCA based circuit. Using this algorithm we can easily calculate the potential energy for each DOT in a QCA cell. Later on the stability for any particular polarization can be measured form the obtained energy. The potential energy model in this literature will make the complex simulation less error prone as because this is purely based on mathematical analysis.

Let us consider a QCA cell shown in Fig. 1(a). Each QCA cell consists of four dots. Extra electrons remain confined in any two of these dots. Here in the figure four dots are numbered A, B, C, and D respectively. The electron can align themselves either in A and C or in B and D. We will calculate the potential energy of electron in positions A, B, C and D. Our objective is to find out the total potential energy at (A+C) and (B+D). If it is observed that the energy at (A+C) is less than that at (B+D), then it can be concluded that the electron will acquire position A and C, because it has more stability. Otherwise vice versa is stable.

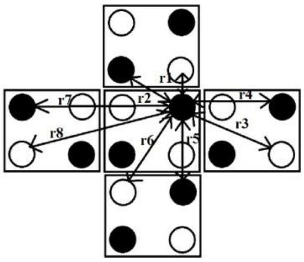

Fig. 4. Distance of electron 'A' from neighbouring DOTs

In Fig. 4, the distance of electron A from its neighbouring DOTs are denoted by r1, r2, r3, r4, r5, r6, r7 and r8 respectively. The potential energy between two electrons is calculated using the equation (2) [Navi et al (2010)].

$$U = \frac{kQ1Q2}{r} \tag{2}$$

Where, $kQ1Q2 = 23.04 \times 10^{-29} = A$, Here k is known as Kink Energy, $Q1, Q2$ are the electronic charges and r is the distance between them [Navi et al (2010)]. This is called radius effect [Sarkar and Chattopadhyay (2014)]. Now the algorithm to find out the polarization of any QCA cell after columbic interaction with neighbouring cell is given below:

Algorithm

```
# Calculation of potential energy
Begin
  1. Input U0 = 0
  2. Select a cell randomly
  3. Select a dot randomly of selected cell
  4.    Check for neighbouring cell present or not
  5.       IF not Then go to 15
  6.             Do for i=1 to 4 in step of 1 do
  7.                Select neighbouring electron
  8.                  Find distance between that two dots
  9.                  CALCULATE ENERGY = U1 using equation-2
  10.                   U1 = U1+U0
  11.                   U0 = U1
  12.                 GO TO NEXT DOT
  13.                GO TO 7
  14.              End for
  15.      GO TO 4
  16.   THE TOTAL ENERGY FOR THAT DOTS = U0
  17.   Take another dot of the randomly selected cell
  18.   Calculate U0 for that dot
  19.   Do this for A, B, C and D dots.
  20.   Calculate total energy of (A+C) and (B+D).
  21.   Check which one is higher.
  22.   LOWER VALUE WILL STABLE.
End
```

Using this algorithm it is possible to find out the polarization of any QCA cell accurately even for complex designs. Using this algorithm we can find the working of QCA tile based XOR gate in the next section.

3. Working of QCA Tile based XOR

Fig. 5 shows the tile structure based XOR gate. A, A bar, B and B bar are the four inputs. Apart from that there are three fixed cells (a, b and c). These fixed cells if placed a, b and c with polarization -1, +1 and +1 respectively, then the tile structure will act as a XOR gate. Here we have marked three intermediate cell x, y and z. We will first calculate the potential energy in x due to the effect of input cells A and B and one fixed cell at b=+1 polarization. Next the potential energy of cell y is calculated due to the effect of A bar, B bar and fixed cell at a=+1 polarization. Finally we will calculate the potential energy of cell z due to the effects of x and y and third fixed polarized cell at c= -1 polarization. The polarization of the z cell will determine the polarization of the output cell A XOR B. It is to be noted that each of the cell x, y and z have the four dots as A, B, C and D as in the shown in Fig. 5.

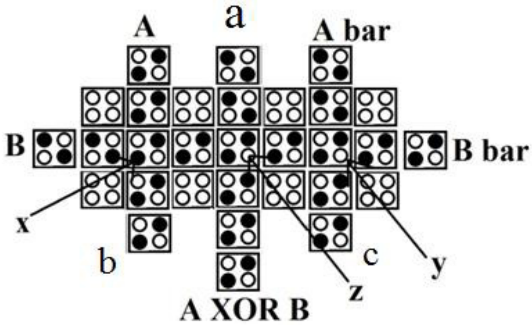

Fig. 5. Tile structured QCA based XOR gate

Let us consider the case when input A is at +1 polarization and Input B is at -1 polarization. The total potential energy of electron A of cell x is obtained by the following calculation:

$$U1 = \frac{A}{r1} = \frac{23.04\times10^{-29}}{20\times10^{-9}} \approx 1.15\times10^{-20} \tag{3}$$

$$U2 = \frac{A}{r2} = \frac{23.04\times10^{-29}}{14.10\times10^{-9}} \approx 1.63\times10^{-20} \tag{4}$$

$$U3 = \frac{A}{r3} = \frac{23.04\times10^{-29}}{29.58\times10^{-9}} \approx 0.77\times10^{-20} \tag{5}$$

$$U4 = \frac{A}{r4} = \frac{23.04\times10^{-29}}{22.03\times10^{-9}} \approx 1.04\times10^{-20} \tag{6}$$

$$U5 = \frac{A}{r5} = \frac{23.04\times10^{-29}}{18.72\times10^{-9}} \approx 1.23\times10^{-20} \tag{7}$$

$$U6 = \frac{A}{r6} = \frac{23.04\times10^{-29}}{30.91\times10^{-9}} \approx 0.74\times10^{-20} \tag{8}$$

$$U = \sum_{n=0}^{i} U_i \tag{9}$$

So, $U_A \approx 6.56\times10^{-20} J$. Similarly we found $U_B \approx 7.96\times10^{-20} J$, $U_C \approx 8.01\times10^{-20} J$ and $U_D \approx 6.99\times10^{-20} J$. Finally we found the potential energy of DOT (A+C) $\approx 14.66\times10^{-20} J$ and for DOT (B+D) $\approx 14.95\times10^{-20} J$. Hence, potential energy of DOT (A+C) < potential energy of DOT (B+D), which concludes that the polarization of cell x is +1. Similarly we can determine the potential energies of y and finally z due to x, y. Using A = +1 and B = -1 we find the potential energy of DOT (A+C) $\approx 14.56\times10^{-20}J$ and for DOT (B+D) $\approx 14.95\times10^{-20}J$ of the cell z. We know that lower value will stable. So we can say that the polarization of z and hence the output (A XOR B) will be +1. Other cases can be obtained similarly, which are shown in Table-1.

Table 1. Potential Energy for cell x, y and z of QCA based tile XOR gate.

Inputs	cell	dot	Potential energy (10^{-20} J)	Total potential energy (A+C)	Total potential energy (B+D)
A=+1, B=-1	x	A	6.65		
		B	7.96		
		C	8.01	14.66	14.95
		D	6.99		
	y	A	8.01		
		B	6.6		
		C	6.55	14.56	14.95
		D	8.35		
	z	A	8.01		
		B	6.6		
		C	6.55	14.56	14.95
		D	8.35		
A=-1,B=+1	x	A	8.01		
		B	6.6		
		C	6.55	14.56	14.65
		D	8.35		
	y	A	6.65		
		B	7.96		
		C	8.01	14.66	14.95
		D	6.99		
	z	A	8.01		
		B	6.6		
		C	6.55	14.56	14.95
		D	8.35		
A=+1,B=+1	x	A	6.7		
		B	8.3	13.4	15.29
		C	6.7		
		D	6.99		
	y	A	9.64		
		B	7.67		
		C	6.94	16.58	15.34
		D	7.67		
	z	A	6.6		
		B	8.01		
		C	8.35	14.95	14.56
		D	6.55		
A=-1,B=-1	x	A	9.64		
		B	7.67		
		C	6.94	16.58	15.34
		D	7.67		
	y	A	6.7		
		B	8.3		
		C	6.7	13.4	15.29
		D	6.99		
	z	A	6.6		
		B	8.01		
		C	8.35	14.95	14.56
		D	6.55		

We can easily determine which having the higher and lower potential from the difference between calculated potentials of (A+C) and (B+D) from Table-1. We define this parameter as $\Delta|_i$, i.e.,

$$\Delta|_i = \{\text{potential energy } (A+C) - \text{potential energy } (B+D)\} \tag{10}$$

Where, $i \in \{X, Y, Z\}$. If $\Delta|_i < 0$ then polarization states of '*i*-th' cell ($\Delta_P|_i$) = +1 and if $\Delta|_i > 0$ then polarization states of '*i*-th' cell ($\Delta_P|_i$) = -1. The variation of $\Delta|_i$ and $\Delta_P|_i$ for different input (AB) combinations of the cell $i = X, Y$ and Z is plotted in Fig. 6.

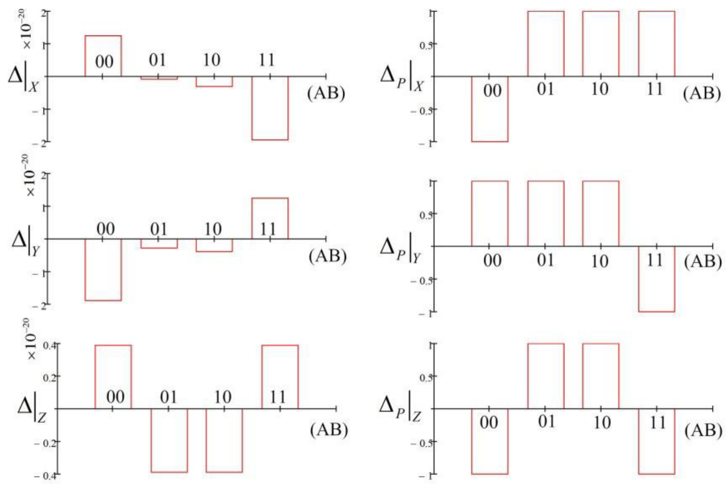

Fig. 6. The variation of (a) $\Delta|_i$ and (b) $\Delta_P|_i$ for different input (AB) combinations ($i \in \{X, Y, Z\}$).

The same design has been done in QCADesigner, (the QCA layout is shown in Fig. 7(a)). We simulate the same design and get the results ($\Delta_P|_X$, $\Delta_P|_Y$ and $\Delta_P|_Z$), which are shown in this Fig. 7(b). Also (A XOR B) output simulated result is shown. The results perfectly match with the calculated values shown in Fig. 6. The applied clock is 9.8×10^{-22} sec in high level and 3.8×10^{-23} sec in low level. Similarly we can calculate data flow in different QCA based structures easily without error.

Fig. 7. (a) QCADesigner layout of tile structure based XOR gate; (b) Simulated $\Delta_P\big|_i$ ($i \in \{X, Y, Z\}$) and (A XOR B) by QCADesigner.

4. Conclusion

QCA cell exists at very low temperature. So designers have to solely depend on the simulation based data to evaluate the working of QCA. For bigger and complex circuits the simulation result becomes unpredictable. For this reason we have proposed the algorithm of QCA data flow, which only based on columbic interaction between neighboring cells. In this algorithm we have calculated the potential energy of the electron in any particular DOT and thus determined the stability of the electron in that DOT. By this method we can accurately find out the position of electron in any QCA cell which will further tell us the polarization or the digital value that the cell will hold.

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